Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Physics B (Proc. Suppl.) 138 (2005) 370–375
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

Long baseline neutrino oscillations and leptonic CP violation

William J. Marciano[a]*

[a]Brookhaven National Laboratory,
Upton, New York 11973

The status of 3-generation lepton mixing is reviewed. Future possible neutrino facilities using: *i*) intense conventional $\overset{(-)}{\nu}_\mu$ sources, *ii*) superbeams and *iii*) neutrino factories are discussed. Properties of CP-violating asymmetries are described. It is shown that our ability to measure the CP-violating phase δ is rather insensitive to the specific value of θ_{13} for $0.01 \leq \sin^2 2\theta_{13} \lesssim 0.20$, as well as the detector distance (for very long distances). The potential for making precision measurements of all neutrino oscillation parameters (θ_{ij}, Δm^2_{ij}, δ) using a wide band ν_μ beam is explained using results of a Brookhaven-Homestake (2540km) study. An outlook on the future is given.

1. STATUS OF 3-GENERATION LEPTON MIXING

The known weak interaction states $|\nu_\ell>, \ell = e, \mu, \tau$ produced in charged current interactions are related to the neutrino mass eigenstates $|\nu_i>, i = 1, 2, 3$ with masses m_i by the 3×3 unitary matrix U.

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \tag{1}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

Studies of atmospheric and $K2K$ $\nu_\mu \to \nu_\mu$ disappearance at the Super-Kamiokande (SK) detector indicate [1]

$$\Delta m^2_{32} = m^2_3 - m^2_2 = \pm 2.0^{+1.0}_{-0.7} \times 10^{-3}\mathrm{eV}^2 \tag{2a}$$

$$\sin^2 2\theta_{23} \simeq 0.85 - 1.0 \tag{2b}$$

The sign of Δm^2_{32} is not determined. For $m_3 > m_2$, normal ordering, neutrinoless double beta decay is highly suppressed, while for $m_2 > m_3$, inverted hierarchy, it could be potentially observable in the next generation of proposed experiments. So determining the sign of Δm^2_{32} is a high priority. In the case of θ_{23}, maximal mixing, $\theta_{23} \simeq 45°$ is favored. How close that angle is to 45° is an important issue for model building. A very precise measurement is strongly warranted.

The value of Δm^2_{32} has been declining over the years, with recent changes [1] $3.0 \to 2.5 \to 2.0 \times 10^{-3}\mathrm{eV}^2$ sending chills up the spines of some proposers of future oscillation experiments. The change is actually good news for very long baseline experiments, $L \simeq$ 2000–4000km, of the type I will discuss.

Solar neutrino ($\nu_e \to \nu_e$ and $\nu_e \to \nu_x$) oscillation experiments and the Kamland reactor study of $\bar{\nu}_e$ disappearance [2] prefer

$$\Delta m^2_{21} = m^2_2 - m^2_1 = 7.3 \pm 1 \times 10^{-5}\mathrm{eV}^2 \tag{3a}$$

$$\sin^2 2\theta_{12} \simeq 0.84 \pm 0.10 \tag{3b}$$

The angle θ_{12} is large but not maximal.

Within the 3-generation formalism, what remains to be determined is the value of θ_{13}, which is currently bounded [3]

$$0 \leq \sin^2 2\theta_{13} \lesssim 0.20 \tag{4}$$

by reactor experiments, along with the phase, δ, about which nothing is currently known

$$0 \leq \delta < 2\pi. \tag{5}$$

*This work is supported by the U.S. Department of Energy under contract number DE-AC02-98-CH-10886.

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2004.11.085

After those parameters are determined, one will have an intrinsic measure of CP violation via the Jarlskog invariant [4]

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta. \quad (6)$$

From the known angles ($\sin^2 2\theta_{12} \approx 0.8$, $\sin^2 2\theta_{23} \simeq 1$)

$$J_{CP} \simeq 0.23 \sin\theta_{13} \sin\delta, \quad (7)$$

which suggests it is potentially enormous in comparison with the quark CKM matrix value

$$J_{CP}^{CKM} \simeq 3 \pm 1 \times 10^{-5}. \quad (8)$$

Besides determining the Δm^2_{ij}, their signs, θ_{ij} and δ as precisely as possible, one would also like to have precision redundancy in those studies which probes deviations due to "new physics" such as sterile neutrino mixing, effects of extra dimensions, exotic neutrino interactions with matter, etc.

It appears from detailed studies [5] that a measurement of δ (which requires $\theta_{13} \neq 0$) and J_{CP} will need: 1) a 1–4 megawatt proton source capable of producing an intense neutrino beam, 2) a very large proton decay class detector with fiducial mass between several hundred and a thousand kilotons and 3) a long run of 5–8 $\times 10^7$ sec. The second of these suggests a natural marriage of the next generation of long baseline neutrino oscillation and proton decay experiments. The latter will also search for supernova and atmospheric neutrinos, magnetic monopoles, n-$\bar{n}$ oscillations, etc. Such a large multifaceted detector will be a facility capable of revolutionary discoveries and a diverse physics program. The required intense neutrino beam can be realized in various ways that will be compared in the next section.

2. FUTURE NEUTRINO BEAMS

2.1. Intense Conventional Beams:

Conventional neutrino beams are made with proton beams on a target [6]. The produced pions are focused electromagnetically using a so-called horn device. The pion beam then decays, $\pi^+ \to \mu^+\nu_\mu$ (or $\pi^- \to \mu^-\bar{\nu}_\mu$) in a long tunnel (length determined by the E_ν requirements). Neutrino horns are very efficient, producing about $0.15\nu_\mu/24$ GeV proton on target. So, if we were to run the current AGS ($E_p = 24$ GeV, $I_p = 4 \times 10^{13} p/\text{sec} \to 0.14$ MW power) with a 200 m decay tunnel, we would produce a broad band beam [6,7] of about $6 \times 10^{12}\nu_\mu/\text{sec}$ with its main support in the energy region 0.5 GeV $\lesssim E_\nu \lesssim 5$ GeV and peak near 1.5 GeV. Increasing the power of the AGS to about 1 MW is straightforward. It requires a new 1.2 GeV linac injector to replace the booster [7]. Such a change would increase the neutrino flux by about a factor of 7 and could be easily upgraded by another factor of 2 (to 2 MW) if needed. Targetry for a 1 MW source and horn focusing are rather conventional; so such an intense neutrino beam requires little R&D. It could be built rather quickly. At the AGS, we would place the 200 m pion decay tunnel on a constructed hill. The cost for constructing such a hill is much cheaper than making a hole in the ground [7]. The experiment we propose would send the beam 2540 km to a detector at Homestake or some comparable location (2000–4000 km).

2.2. Superbeams:

By definition, a neutrino superbeam would require a 4 MW or more proton driver. Such a facility would deliver 4 times as much neutrino flux as a more conventional 1 MW source. However, because of heat and increased radiation loads, it would require liquid targets, robotic handling and special focusing horns or solenoids. The engineering requirements for 4 MW are much more demanding, requiring significant R&D to be realized. The cost for such a facility would be much higher than the more conventional 1 MW proton driver and horn described above. Preliminary discussions of 4 MW sources for neutrino superbeams and their anticipated oscillation studies are [8,9]

JPARC (Phase II) $\to$

$$\text{Hyper K (1000 kton } H_20) \quad L = 295km$$

CERN (Super linac) $\to$

$$\text{Frejus (1000kton } H_20) \quad L = 130km.$$

Because of the relatively short distances, those proposals would employ the low-energy neutrino flux $E_\nu < 1$ GeV for their oscillation studies. That corresponds to only a fraction of the potentially available neutrino flux and the cross section is lower. To compensate, they must employ enormous detectors (1000 Kton), a more powerful source, and long running time. Our working group at Brookhaven has argued that it is much more cost effective and richer in physics to use a wide-band beam of neutrinos and a much longer detector distance [10].

2.3. Neutrino Factory:

Starting with an intense proton beam on target, the neutrino factory concept envisions capturing the $\mu^\pm$ from $\pi^\pm \to \mu^\pm \nu$ decays, cooling them and then accelerating them to 20–50 GeV. At that point they are placed in a storage ring with long straight sections where the decays $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ or $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ produce clean fluxes of high energy neutrinos with $< E_\nu > \simeq 0.7$–$0.8 E_\mu$. Neutrino factories are expected to yield about $0.03\nu_\mu$/proton; i.e., about 1/5 the flux of a conventional horn focused neutrino beam. The neutrino factories advantage (if it can be utilized) is the higher energy [11]. The beam solid angle will be $\sim 1/E_\mu^2$ and deep inelastic cross sections grow as E_ν. Hence, at fixed distance one can gain $\sim E_\mu^3$ in statistics because of higher energies. That factor is spectacular for conventional neutrino physics. In the case of oscillation studies, higher energies implies longer distance requirements and a flux fall-off by $1/L^2$. That means, for $E_\nu \simeq 20$ GeV to sit at the first oscillation peak requires a detector at 12,000 km, which is not possible. Hence, neutrino factories must do their studies primarily at shorter distances (~ 3000 km) where the first oscillation is only fractional. For measuring θ_{13}, the relative nearness is not a problem, but it is a drawback for CP violation studies which are optimized at oscillation peaks. If θ_{13} is extremely small $\sin^2 2\theta_{13} \lesssim 0.003$, neutrino factories may be our only hope to measure it. However, in that case, CP violation and the phase δ will be difficult to determine with such a facility.

3. CP VIOLATION

The flavor-changing oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ have a very rich structure. The oscillation probability is given by 3 important contributions, as well as matter effects and smaller terms

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e) \quad (9)$$

$$+ \text{ matter effects } + \text{ smaller contributions,}$$

where [5]

$$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) \quad (10a)$$

$$P_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13} \sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right] \quad (10b)$$

$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right), \quad (10c)$$

while for $\bar{\nu}_\mu$, $\delta \to -\delta$ and matter effects are changed.

The first term, $P_I(\nu_\mu \to \nu_e)$, is particularly important at relatively short-distances where the atmospheric $\Delta m^2_{31} \simeq \Delta m^2_{32}$ effect dominates, while $P_{III}(\nu_\mu \to \nu_e)$ becomes of primary importance at longer distances where Δm^2_{21} takes over. $P_{II}(\nu_\mu \to \nu_e)$ can be viewed as an interference effect that contains the phase, δ, information. The CP-violating asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \quad (11)$$

is given to leading order in Δm^2_{21} (assuming $\sin^2 2\theta_{13}$ is not too small) by

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects.} \quad (12)$$

The form of that expression is very instructive. The asymmetry grows linearly with distance and increases as θ_{13} gets smaller. Of course $|A_{CP}|$ is bounded by 1 so, if it exceeds that value, a breakdown in my assumption about the dominance of P_I is occurring.

The statistical figure of merit [5]

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A_{CP}^2 N}{1 - A_{CP}^2}, \tag{13}$$

where N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events (properly normalized). Since N falls (roughly) as $\sin^2\theta_{13}$ and $A_{CP}^2 \sim 1/\sin^2\theta_{13}$, we see that, to a first approximation, the F.O.M. is independent of $\sin\theta_{13}$. Similarly, for a given E_ν the neutrino flux and, consequently, N falls as $1/L^2$ but that is cancelled by L^2 in A_{CP}^2. So, to a good approximation, our ability to measure CP violation is insensitive to L and the value of θ_{13} (if it is not too small). That means we can determine the experimental requirements to measure CP violation without knowing the value of θ_{13}. It also implies that, for very long distances, our ability to measure CP violation is insensitive to the specific distance. Indeed, on that basis, we have argued that for a BNL wide-band beam experiment, all $L \simeq$ 2000–4000 km are roughly of equal merit [10]. Note, for narrow band beams, A_{CP} is optimized at oscillation peaks.

Another way of seeing the insensitivity to L in determining δ is to consider the 3 terms in eq. (10) separately. Each contributes to $\nu_\mu \to \nu_e$ oscillations. The number of events from P_I falls as $1/L^2$ due to flux reduction, while those from P_{II} fall as $1/L$, and from P_{III} they are approximately constant (assuming $sin\frac{\Delta m_{21}^2 L}{4E_\nu} \sim \frac{\Delta m_{21}^2 L}{4E_\nu}$). Viewing P_I and beam-induced backgrounds (which also fall as $1/L^2$) together as a total background for measuring P_{II} and P_{III}, we see that the determination of P_{II} and therefore δ relative to those backgrounds is independent of L for fixed E_ν, while the P_{III} signal to background increases linearly with L. So longer distances have some advantages. For that reason, along with matter enhancement effects, larger E_ν high-energy cross sections, larger total neutrino flux, etc., we advocate a wide-band neutrino beam (at $0°$) $0.5 \lesssim E_\nu \lesssim 5$ GeV and a large detector at 2000–4000 km for the measurement of δ. Our study of that idea has shown many added benefits from the very long distance and broad-band beam. Indeed, in principle it allows measurement of Δm_{31}^2, Δm_{21}^2, $sgn\Delta m_{31}^2 \sin^2 2\theta_{12}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{23}$ and δ with outstanding to good precision in one experiment, possibly with only ν_μ running (i.e., no $\bar{\nu}_\mu$). The basic features of that proposal [10] and some of its advantages are outlined below.

4. BNL-HOMESTAKE NEUTRINO OSCILLATION EXPERIMENT

Our working group at Brookhaven National Laboratory (BNL) has written a white paper [7] and several follow-up studies [10] extolling the virtues of a very long baseline BNL-Homestake (2540 km) neutrino oscillation experiment. (Actually, any distance from about 2000–4000 km will do.) Its basic requirements are: 1) A conventional horn focused intense ν_μ beam using an upgraded 1 MW AGS proton beam on a standard target. The cost and technical requirements [7] needed for the upgrade are modest in comparison with ideas for 4 MW sources being discussed. The resulting neutrino beam (on axis at $0°$) would be broad band, 0.5 GeV $\lesssim E_\nu \lesssim$ 5 GeV, peaking near 1.5 GeV. 2) The detector would be about a 500-kton water Cerenkov detector and would likely be somewhat modular in design. This is again modest (about half the cost) in comparison with the 1000 kton behemoth detectors being considered by others. To reconstruct the neutrino energy on an event-by-event basis, we would only use quasi-elastic events $\nu_\mu n \to \mu^- p$ or $\nu_e n \to e^- p$ in the analysis. They represent less than 1/4 of all neutrino events; therefore, a detector with better resolution and acceptance such as liquid Argon or Scintilator could be smaller, in principle, of order 100–200 kton by using a larger fraction of events to do the job. 3) The run time would be about 5×10^7 sec with a ν_μ beam. Two types of oscillation measurements would be made $\nu_\mu \to \nu_\mu$ disappearance and $\nu_\mu \to \nu_e$ appearance. At a later time $\bar{\nu}_\mu$ studies might be carried out; however, they may not be necessary because the wide-band beam allows sensitivity to all neutrino oscillation parameters, even δ, without actually measuring a CP-violating effect such as A_{CP} directly. Instead a fit is done to the data assuming 3-generation mixing.

Because of the long distance and broad-band beam, many physics studies are possible. The measurement of $\nu_\mu \to \nu_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + \text{smaller terms} \tag{14}$$

over the range $0.5 \le E_\nu \le 5$ GeV would be sensitive to 3 oscillation cycles [10]. The lower energies (several oscillation cycles) are particularly sensitive to Δm^2_{31}. Such measurements would determine $\sin^2 2\theta_{23}$ and Δm^2_{31} to better than $\pm 1\%$ statistically. Energy calibration will be the major systematic uncertainty. Such a study will tell us if $\theta_{23} \simeq 45°$ to within about $\pm 2°$. Also, by comparing values of Δm^2_{31} obtained at different E_ν, one can search for indications of "new physics".

The study of $\nu_\mu \to \nu_e$ oscillations can be divided into three domains: 1) high energy, 3 GeV $\le E_\nu \lesssim$ 5 GeV; 2) intermediate energy, 1 GeV $\le E_\nu \le$ 3 GeV; and 3) low energy, $E_\nu \lesssim 1$ GeV. Roughly speaking, the high-energy ν_e events will be matter enhanced (suppressed) for the normal (inverted) mass hierarchy. The effect is very pronounced [10], making a determination of the sign of Δm^2_{31} relatively easy (for $\sin^2 2\theta_{13} \ge 0.01$) and allowing for a good measurement or bound on θ_{13} (via P_I) which is better than any other proposed experiment [10]. Intermediate energy events will measure both $\sin\delta$ and $\cos\delta$ via P_{II}. In that way, we expect δ to be determined to within ± 15, independent of its value with no ambiguity [10] (again assuming $\sin^2 2\theta_{13} \gtrsim 0.01$). That type of δ determination is more robust and statistically more powerful than A_{CP}. Finally, the low energy ν_e events will determine the combination $\Delta m^2_{21} \sin 2\theta_{12}$ to about $\pm 5\%$ via P_{III}. Altogether, this single experiment will measure or constrain all parameters of 3-generation leptonic mixing with unprecedented sensitivity. It would put leptonic mixing on about the same level of precision as quark mixing. Specific detains of detector optimization and running strategy still need to be ironed out, but the basic idea of determining all oscillation parameters via one experiment is very compelling.

5. OUTLOOK

It appears that the combination of intense conventional wide-band ν_μ beam, large detector and very long baseline provides an opportunity to measure Δm^2_{31}, sign Δm^2_{31}, Δm^2_{21}, all θ_{ij} and δ with good to high precision. The intense proton source required for this effort is a straightforward upgrade of the AGS. The large detector (~ 500 kton H_2O) could be sited almost at any of the national underground lab sites being considered (Homestake, Henderson, WIPP, etc.). It would also search for proton decay, supernova and atmospheric neutrinos, etc. to unprecedented levels. The facility would probably be at the forefront of particle physics research for 50 years or more.

What remains to be done? Detector R&D to reject backgrounds such as π^0 and reduce the cost are needed. Of course, an underground lab site needs to be developed and the horn-generated beam flux should be optimized. After the first phase of ν_μ is completed, one might run $\bar{\nu}_\mu$ for a few years if one wants to actually observe CP violation (rather than just a determination of δ) or if an inverted mass hierarchy turns out to be correct. During that time further upgrades of the AGS to 2 MW or more might be appropriate.

The strategy for long baseline neutrino oscillations outlined here is based on a novel concept broad-band beam, very long distance and large detector. It is bold, ambitious and doable. The opportunity is within our grasp and should be seized.

REFERENCES

1. Y. Hayato, HEP2003 talk, Aachen Germany July 2003. For a review see V. Barger, D. Marfatia and K. Whisnant, Int. J. Mod. Phys. E 12 (2003) 569.
2. SNO Collaboration, Q. Ahmad *et al.*, nucl-ex/0309004; A. Balantekin and H. Yuksel, hep-ph/0309079.
3. CHOOZ: M. Apollonio *et al.*, Phys. Lett. B

466 (1999) 415; Palo Verde, F. Boehm *et al.*, Nucl. Phys. Proc. Suppl. 91 (2001) 91.
4. C. Jarlskog, Z. Phys. C 29 (1985) 491; Phys. Rev. D 35 (1987) 1685.
5. W. Marciano, Extra Long Baseline Neutrino Oscillations and CP Violation, hep-ph/0108181.
6. D. Beavis *et al.*, BNL Report 52459, AGS proposal 889.
7. BNL Neutrino Working Group: M. Diwan *et al.*, hep-ex/0211001.
8. Y. Itow *et al.*, The JHF-Kamioka Neutrino Project, hep-ex/0106019.
9. B. Autin *et al.*, (SPL Study Group) CERN 2000–012 (2000) Report.
10. M. Diwan *et al.*, Phys. Rev. D 68 (2003) 012002.
11. Physics at a Neutrino Factory, C. Albright *et al.*, hep-ex/0008064; Z. Parsa, “Neutrino Factories-Physics Potential”, AIP Conference Proceedings 549, Intersections of Particle and Nuclear Physics, Quebec City (2000) p. 781.